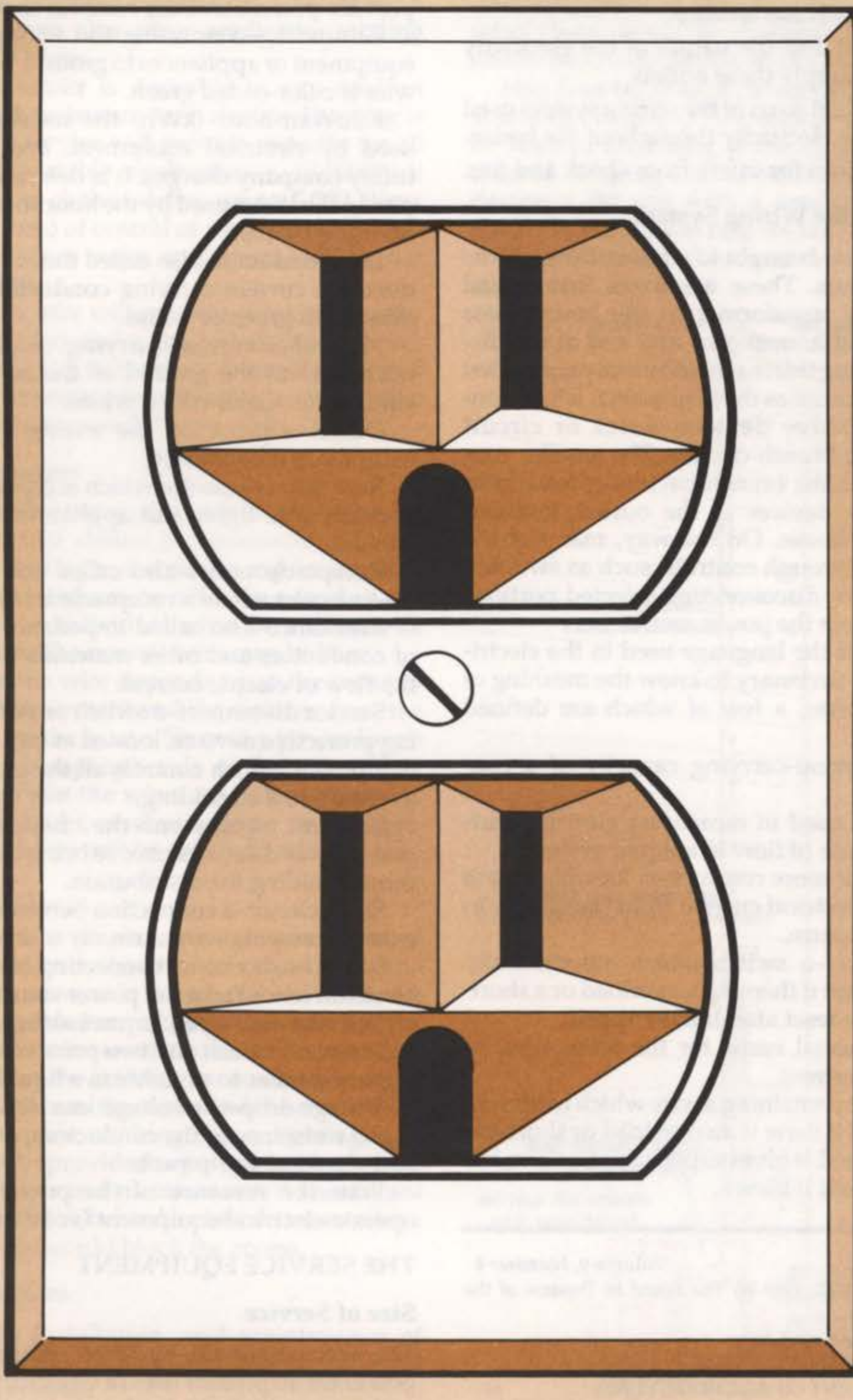
University of Illinois at Urbana-Champaign
Small Homes Council-Building Research Council

COUNCIL NOTES



G4.2 ELECTRICAL WIRING

Electrical Wiring G4.2 Volume 9 Number 4

This circular is intended to be used as a guide in planning the electrical system for a new home or as a basis for checking the electrical system in an existing house. It is primarily concerned with four aspects of electrical use and planning.

- The location and selection of electrical outlets for maximum convenience.
- The amount and the nature of the electricity needed to supply these outlets.
- The individual parts of the wiring system used to distribute electricity throughout the house.
- The provisions for safety from shock and fire.

Introduction to the Wiring System

Electrical power is brought to a house through the service conductors. These are wires that extend from the utility transformer to the house, pass through the Watt-hour meter, and end at the disconnect. Following this is a distribution panel, often in the same enclosure as the disconnect, which contains the protective devices (fuses or circuit breakers) for the branch circuits. The smaller conductors used for the branch circuits extend from these protective devices to the outlets installed throughout the house. On the way, many of the wires will pass through controls, such as switches or relays, to allow disconnecting selected portions of the circuits from the power source.

To understand the language used in the electrical industry, it is necessary to know the meaning of many special terms, a few of which are defined here.

Ampacity–current-carrying capacity of a conductor.

Ampere–unit used in measuring electrical current, similar to rate of flow in a liquid system.

Circuit–two or more conductors forming a path for the flow of electrical current from the supply to the outlets and return.

Circuit breaker–a switch which automatically turns off the circuit if there is an overload or a short-circuit. It may be reset after it has tripped.

Conductors–usual name for the wires used to carry electrical current.

Fuse–a device containing a wire which melts and opens the circuit if there is an overload or short-circuit. Properly sized, it gives superior protection, but it must be replaced if blown.

COUNCIL NOTES Volume 9, Number 4

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Ground–the earth or a conducting material connected to the earth.

Ground fault–an unintentional connection between a current-carrying conductor and ground.

Ground-fault circuit interrupter (GFCI)–a device used in addition to a circuit breaker or fuse to provide protection from harmful shock.

Grounding–connecting the wiring system and equipment or appliances to ground. The grounding wire is color-coded green.

KiloWatt-hour (kWh)–the measure of energy used by electrical equipment, and the basis for utility company charges. It is determined by multiplying the Watts used by the hours of operation and dividing by 1000.

Line conductor–also called the hot or phase conductor–a current-carrying conductor, color-coded other than green or white.

Neutral–a current-carrying conductor that is connected to the ground in the service entrance equipment. Color-coded white.

Outlet–a point on the wiring system where equipment is connected.

Receptacle–a device which accepts plugs to connect portable lights and appliances to the branch circuits.

Receptacle outlet–also called convenience outlet–an outlet where a receptacle is installed.

Resistance–also called impedance–the property of conductors and other materials which opposes the flow of electric current.

Service disconnect–a switch or switches, including protective devices, located as part of the service equipment, which controls all the electrical power available to the building.

Service equipment–the necessary wiring materials and devices used to bring electrical power into a building for distribution.

Short circuit–a connection between two or more current-carrying wires, usually unintentional.

Switch–a device for connecting or disconnecting electrical loads from the power source.

Volt–the unit used in measuring the potential difference between any two points on the electrical system–similar to pressure in a liquid system.

Voltage drop–the voltage loss which occurs due to the resistance of the conductors, wiring devices, and electrical equipment.

Watt–the measure of the power required to operate electrical equipment (volts x amperes).

THE SERVICE EQUIPMENT

Size of Service

The service should be large enough to provide power for all present uses of electricity in the home, with some provision for future expansion and addition of major appliances.

60-ampere service was formerly the minimum acceptable according to the National Electric Code. This service provides sufficient capacity for lighting and portable appliances, including a range, *or* a clothes dryer, *or* a water heater, but no additional major appliances can be added. Under no circumstances is this size service adequate for a house larger than 1000 square feet.

100-ampere service is the current required minimum service for homes. It provides capacity for lighting and portable appliances, including a 10,000-Watt range plus other appliances totaling less than 8,000 Watts.

150-ampere service is desirable in any modern house in which resistance-type electrical heating is not used. This service will provide capacity for all lighting and portable appliances, a 13,500-Watt electric range, a clothes dryer, up to 5,000 Watts (three to five tons) of central or room air conditioning, plus any other major appliances totaling not over 8,200 Watts.

200-ampere service will provide capacity to carry all the loads listed under the 150-ampere service, plus electric heating. In the case of very large homes heated with resistance-type heating, it is possible that a larger service would be needed.

Service Conductors

Service conductors from the power source to the service equipment should be three-wire, 120-240-volt, sized according to the power requirements of the house. The wires can be either in a conduit underground or as individual wires or a three-wire cable overhead. The neutral wire may be bare.

The size of the wire depends upon the capacity of the service equipment and the distance from the power source to the house. Since any power loss is on the power company's side of the meter, they usually ensure that the wires are of adequate size. If there is any doubt, an electrician or power company representative will be able to check.

The Disconnect

Consisting of one to six circuit breakers, fused switches, or pullouts, the disconnect is sized to the capacity of the service. It must be located where it is readily accessible for quick operation, and at the nearest possible point to where the service entrance conductors enter the building, or on the exterior of the building between the meter and the entry to the building. Adequate working space, lighting, and marking must be provided to permit quick, easy access for operation and maintenance. It should not be located in a closet, behind locked doors, or where stored materials would block the access.

Protective Devices

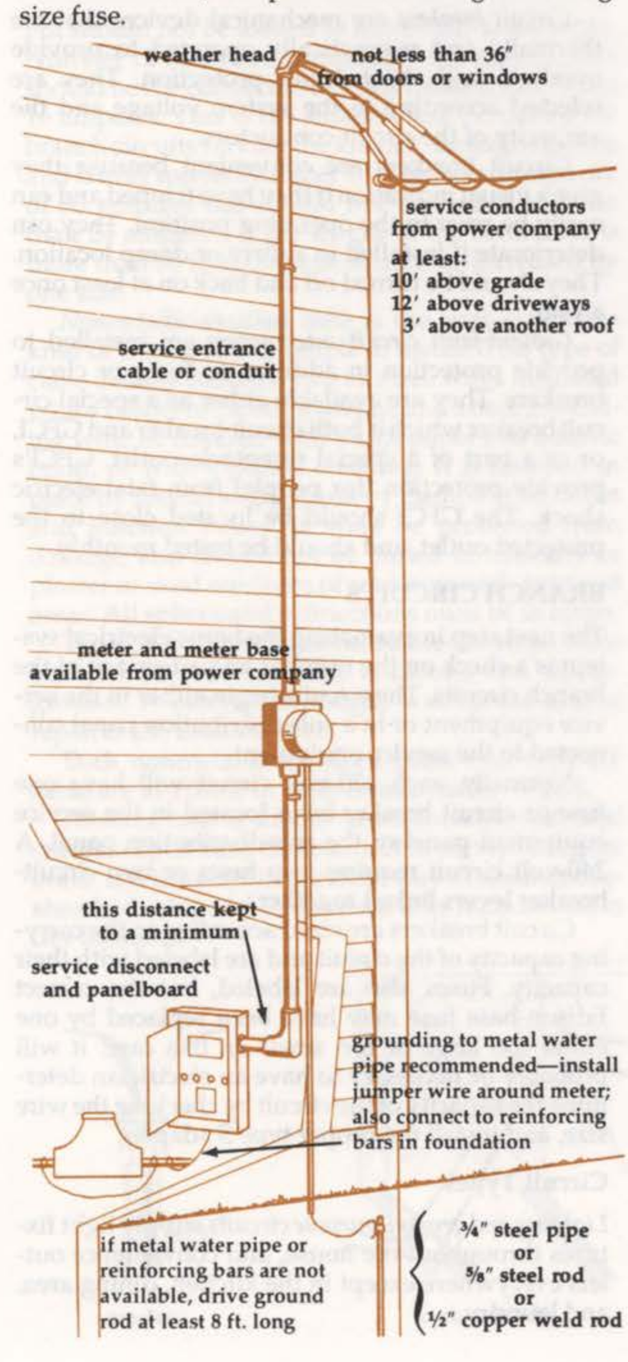
The selection, installation, and maintenance of protective devices is critical to the safe operation of any electrical system.

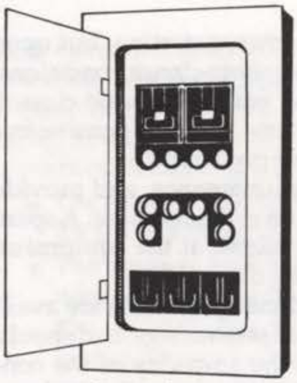
Cartridge fuses are available in standard sizes from 15 to 600 amperes. They are selected according to the ampacity of the circuit conductors.

It is recommended that class K-5 be selected for use in a service disconnect. These are dual-element, time-delay fuses that carry short-term overloads, such as the surge from a motor starting, but open with extreme speed under short-circuit conditions. Some panelboards come equipped with class T main fuses. The class H fuse is less expensive but does not provide the same protection.

Fuses do not require maintenance, and provide constant protection over an extended time. A spare set of fuses should be available at the equipment, and blown fuses should be discarded.

Plug fuses for branch circuit protection are available in 15, 20, 25, and 30-ampere ratings, and should be selected according to the ampacity of the conductors. All plug fuses should be type S, which are designed for use with a special adapter that is placed in the Edison fuse socket. This adapter cannot be removed, and prevents installing the wrong size fuse.

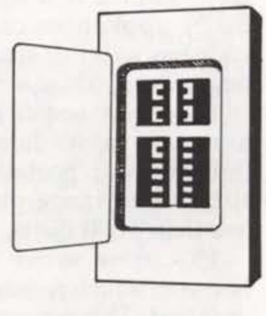




service equipment with fuses

circuit breaker

combination GFCI-circuit breaker



service equipment with circuit breakers

Circuit breakers are mechanical devices that are thermally and magnetically operated to provide overload and short-circuit protection. They are selected according to the system voltage and the ampacity of the circuit conductors.

Circuit breakers are convenient because they give a visual indication if they have tripped and can easily be reset to the operating position. They can deteriorate if installed in a dirty or damp location. They should be turned off and back on at least once a year.

Ground-fault circuit interrupters are installed to provide protection in addition to fuses or circuit breakers. They are available either as a special circuit breaker which is both circuit breaker and GFCI, or as a part of a special receptacle outlet. GFCI's provide protection (for people) from fatal electric shock. The GFCI should be located close to the protected outlet, and should be tested monthly.

BRANCH CIRCUITS

The next step in evaluating the home electrical system is a check on the number and adequacy of the branch circuits. The circuits begin either in the service equipment or in a sub-distribution panel connected to the service equipment.

Normally, each 120-volt circuit will have one fuse or circuit breaker lever located in the service equipment panel or the sub-distribution panel. A 240-volt circuit requires two fuses or two circuit-breaker levers linked together.

Circuit breakers are sized according to the carrying capacity of the circuit and are labeled with their capacity. Fuses also are labeled, but the correct Edison-base fuse may have been replaced by one either too large or too small. In this case, it will probably be necessary to have an electrician determine the capacity of the circuit by checking the wire size, and install the proper type S adapter.

Circuit Types

Lighting and general-purpose circuits supply light fixtures throughout the house, and convenience outlets everywhere except in the kitchen, dining area, and laundry.

One 20-ampere, 120-volt general purpose circuit should be provided for each 500 square feet or fraction thereof in the house, or one 15-ampere, 120-volt circuit for each 375 square feet. Outlets supplied by these circuits should be divided equally among the circuits. Each room should be served by more than one circuit, with the lights on a separate circuit from the receptacle outlets.

Appliance circuits provide power for portable appliances in the kitchen, dining room, and laundry. A separate circuit is normally provided for any workshop area. No lighting may be installed on these circuits.

Two 20-ampere, 120-volt appliance circuits should serve the kitchen and dining areas. The laundry must be served by a separate 20-ampere appliance circuit.

Special purpose circuits serve individual permanent installations. The electric range, separate oven, electric clothes dryer, fuel-fired central heating system, central air conditioning system, individual room heaters, dishwasher-waste disposer, electric water heater, and similar equipment require separate circuits.

Circuit Capacity

In order to operate efficiently, electric equipment must be supplied by wires of sufficient size. When a circuit becomes overloaded, excessive power loss occurs, and the wire heats up and may become a fire hazard.

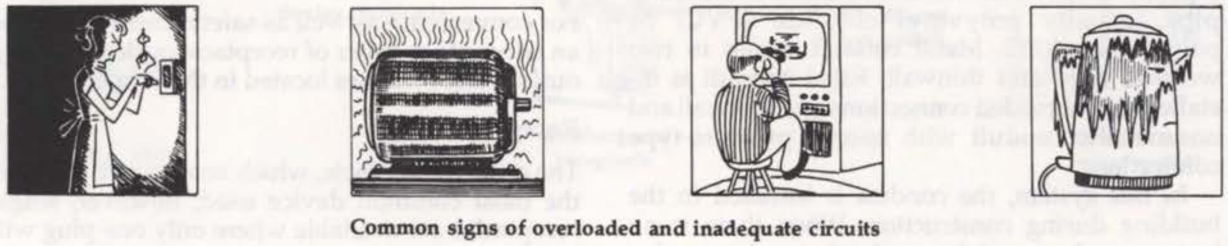
Common signs of an overloaded circuit are:

- Fuses "blow" frequently or circuit breakers trip and must often be reset.
- Toasters, irons, and other heat-producing appliances heat up slowly, sometimes never reach desired temperatures.
- Motors overheat and run slowly.
- Television picture shrinks when appliances are in use.

The power loss in a circuit increases four times when the load is doubled. The cost of the power which is wasted by overloaded circuits will more than pay for an additional branch circuit.

POWER REQUIREMENTS FOR MAJOR APPLIANCES

Range	**10,000-13,500 watts**	**Automatic clothes dryer**	**4,500 watts**
Fuel-fired heating system	**800 watts**	**Water heater**	**2,500-5,000 watts**
Dishwasher-waste disposer	**1,500 watts**	**Water pump**	**300-700 watts**
Room air conditioner (12,000 Btuh)	**1,500 watts**	**Home freezer**	**350 watts**
Automatic washer	**700 watts**	**Built-in bathroom heater**	**1,500-2,500 watts**



Common signs of overloaded and inadequate circuits

Methods and Materials

Most branch circuits begin at the service equipment, but in some installations it is easier and cheaper to run a heavy feeder from the service equipment to a sub-distribution panel, and extend some branch circuits from that panel. For example, a sub-distribution panel is often placed in the kitchen-utility area to supply the special-purpose and appliance circuits serving that area.

The most common wiring system is the three-wire 120/240-volt system. This is really two 120-volt circuits which use a common neutral wire. Either 120 volts or 240 volts can be obtained from this system.

This wiring system permits flexibility in selecting the branch circuit. For example, the two line (hot) conductors can be run with one neutral and one ground wire to a distant junction box, where they are split off, each with a separate neutral and ground connected to the neutral and ground feeders, to supply separate loads. This saves the cost of two wires from the distribution panel to the junction box. Also, the two line conductors may be used without a neutral to serve a 240-volt load, which permits the use of smaller wires for a given installed load.

The size of the branch circuit conductors is an important factor in a satisfactory wiring system. The size of wires used in a house is expressed as a gauge number; the smaller the number, the larger the wire.

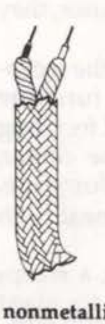
Number 14 wire is the smallest size permitted for a branch circuit. It has an ampacity of 15 amperes but should not be loaded to more than 12 amperes. Number 12 wire has an ampacity of 20 amperes but should not be connected to loads totaling more than 16 amperes. This is the smallest size permitted for branch circuits serving the kitchen, dining, laundry, and family rooms. Number 10 wire has an ampacity of 30 amperes but should not be loaded to more than 24 amperes. If the length of the conductor is more than 50 feet, the wire should be increased by one size.

Nonmetallic-sheathed cable is the least expensive kind of wiring and is simple to install. This type of cable usually contains two or three wires insulated with a rubber or plastic material, and a bare grounding wire, all covered with tough paper and a fabric braid, or with a plastic covering. It is fastened in place by special staples, and by clamps at all outlet and junction boxes. It must be protected from damage, and should not be buried in masonry or plaster or used outdoors or underground, or in wet areas. All splices and connections must be in boxes.

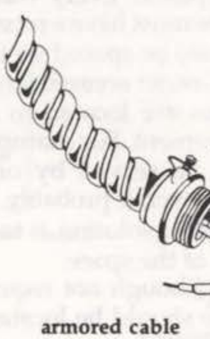
Type UF is similar to nonmetallic-sheathed cable but can be used indoors, outdoors, and underground. A coating of tough, waterproof plastic replaces the braided cover.

Both nonmetallic-sheathed cable and type UF cable are available in sizes from number 14 to 6.

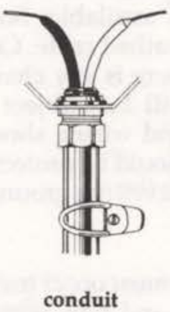
Armored cable is similar to nonmetallic-sheathed cable except it has a flexible steel cover replacing the braid. It is installed in the same way as nonmetallic-sheathed cable and can be used only indoors and in dry locations.



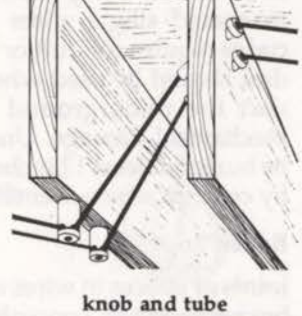
nonmetallic-sheathed cable



armored cable



conduit



knob and tube

Conduit is used where additional protection from mechanical damage is needed and where required by building codes. The most expensive of the wiring systems, it is the most durable.

Conduit is a special grade of aluminum or steel pipe, either galvanized or enameled, or nonmetallic pipe, usually polyvinyl chloride (PVC) or polyethylene (PE). Metal conduit comes in two weights, rigid and thinwall. Rigid conduit is installed with threaded connections and thinwall and nonmetallic conduit with special pressure-type connections.

In this system, the conduit is installed in the building during construction. When there is no longer any danger of the conduit being damaged, a flexible steel tape is pushed through the conduit and is used to pull the required wires into the pipe. Individual, color-coded, insulated conductors are used. The wiring devices are installed after the wires have been pulled into place.

Knob and tube, the oldest of the wiring systems, is no longer approved for new residential work but may be found in older houses. It used single, interior-type, insulated, cambric-covered wires strung on porcelain insulating knobs and cleats and through porcelain tubes. The knobs were nailed to the edges and sides of exposed wood members and had a gripping device to hold the wire in place. Cleats were used to hold the wire where a fixed separation of a pair of wires was required, such as on the side of a joist. If a wire had to pass through a wood member, a hole was bored and a porcelain tube inserted and the wire run through the tube. The wires were no less than three inches apart and one inch from the surface. They were supported every 4 1/2 feet, and all splices and connections were made in metal or plastic boxes.

Surface raceways, made of metal or plastic, are sometimes used for repairs and for new work over solid-core walls and partitions. The outlets and switches are mounted directly on the raceway. The raceways are sometimes made to replace baseboard, door, and corner moldings, and serve as trim as well. A wood molding, cut to the same pattern, is used where wires are not run.

Exterior wiring can be run overhead or underground. Overhead conductors are usually copper or aluminum, coated with a neoprene insulation. Rubber-insulated, cambric-covered wires are found in some older installations. Underground wiring is most economically done with type UF cable. Plastic-coated single wires are also available. Some codes require conduit or lead-sheathed cable. Conduit should be used wherever there is any chance that the underground wire will be subject to mechanical damage. Underground wiring should be buried at least 12 inches and should be protected by conduit where it enters and leaves the ground.

Boxes

Joints or splices in wires or cables must occur inside boxes, except in concealed knob and tube wiring. Also, each switch, convenience outlet, and fixture must be attached at a box. These boxes, used with all types of wiring systems, are made of steel, porcelain, or plastic.

OUTLETS AND SWITCHES

For convenience as well as safety, there should be an adequate number of receptacle outlets, lighting outlets, and switches located in the proper places.

Receptacles

The duplex receptacle, which accepts two plugs, is the most common device used; however, single receptacles are available where only one plug will be used. Receptacles are selected according to the voltage and amperage rating of the circuit. The current rating of the receptacle should be the same as the circuit rating, except a 15-ampere receptacle may be installed on a 20-ampere circuit.

All new 15- and 20-ampere receptacles must be of the grounding type which will accept three-prong plugs. The third prong connects the frame or housing of the appliance to the grounding system. If an old receptacle being replaced was two-prong, and there is no ground wire to connect to the third prong, a GFCI-type receptacle must be used.

Weatherproof receptacles, with watertight covers, are for outdoor locations.

Locking receptacles and plugs are available for overhead outlets and other places where it is desirable to hold the plug securely. They operate by inserting the plug and twisting a quarter-turn. Locking receptacles are useful to prevent accidentally disconnecting appliances such as a freezer.

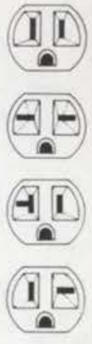
Other special forms of outlets are available. These include receptacle and switch combinations, clock outlets, safety receptacles, dual-voltage units which supply both 120 and 240 volts, and radio and television outlets which also supply antenna and ground connections. Special shapes and designs are used for 240-volt receptacles.

Location of Receptacles

Living rooms, bedrooms, and other general living areas require outlets for lamps, television, and other portable appliances. Enough receptacles should be provided to avoid the use of extension cords. For minimum-quality electrical service, no point along a wall space should be more than six feet from a receptacle. Every wall space more than two feet wide must have a receptacle. For convenience, they should be spaced six to eight feet apart.

Greater accessibility is provided when the receptacles are located to consider probable furniture placement. For example, a wall section 12 feet long can be served by one receptacle in the center. However, it probably will be blocked by furniture. A better solution is to locate receptacles near each end of the space.

Although not required by most codes, a receptacle should be located in each hall area for night lights and cleaning equipment.

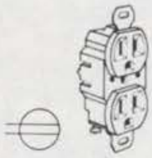


15A, 125V

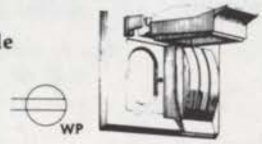
15A, 250V

20A, 125V

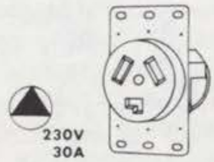
20A, 250V



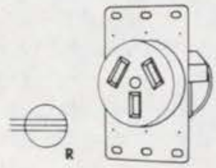
duplex receptacle



weatherproof receptacle



230 v., 30 amp.
(dryer outlet)



230 v., 50 amp.
(range outlet)

At least one receptacle must be installed in each bathroom, and should be located for convenient use of an electric razor and night light. All bathroom receptacles must be GFCI-protected.

In the dining space, an outlet on the appliance circuit may be located 36 inches above the floor so warming and cooking appliances used at the table or buffet can be connected easily.

One receptacle in the laundry area should be located near the drainage and water connections so the washer can be connected. Another should be available for ironing and other activities.

It is recommended that appliance-circuit receptacles be located every 12-36 inches along the working counter area of the kitchen. A multi-outlet strip is suggested. The refrigerator outlet should be 36 inches above the floor. Outlets within six feet of the kitchen sink should be GFCI-protected.

At least one receptacle must be installed in any basement and attached garage, outdoors, and in any attic or crawl space containing equipment which will need service. Garage and outdoor outlets and one outlet in the basement must be GFCI-protected.

Switches

Permanently installed lighting fixtures must be controlled by a switch. Switches may also be used to control convenience outlets. For example, living rooms and bedrooms often have no built-in lighting. Therefore, a receptacle must be switched to control lighting in the room. Duplex outlets can be wired so that only one receptacle is switched, so the other can be used for a clock, radio, or other appliance. Switches are also needed for equipment or appliances which do not have a built-in switch or the switch is inconveniently located.

When walking through the house, it should be possible to light the path ahead and turn off the lights behind without retracing steps. This also applies to outdoor routes between the house and garage and other major areas.

To control a light or receptacle from two places, a three-way switch is needed at each point. To control from three or more places requires two three-way switches and a four-way switch at each of the other locations. Low-voltage switching systems are often used when an outlet is controlled from three or more places.

Multiple switches should be used on hall and passage lights. In bedrooms, it is convenient to have lighting controlled both from near the door and within reach of the bed.

The usual snap switch has copper contact points controlled by a spring which either snaps them together, allowing current to flow, or separates them, halting the current, when the handle is operated. Switches with silver contacts or a mercury tube are quieter and last longer, but are more expensive.

Some switches operate with a touch on a plate or button. Others have lighted handles which glow when the switch is off to serve as locators, or handles that light when the switch is on to serve as an indicator for remote lights, such as in an attic or basement.

S

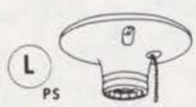
snap switch

S_{WP}

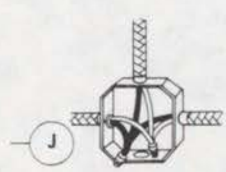
weatherproof switch

S_P

switch with pilot light



pull-chain switch



junction box

In *low-voltage switching systems*, the wall switches control a special low-voltage circuit, which is connected to a relay that operates the line-voltage switch. This allows the use of inexpensive switches and doorbell-type wire on the switching circuit. This system can be expanded so that all the lights in the house can be controlled from one or more master panels, usually located in the master bedroom and/or at the main entrance.

Door switches, which turn on the lights when a door is opened, are used in closets and other spaces without natural light. In less important spaces, such as the basement or storeroom, a pull-chain switch on the fixture may be adequate.

Dimmer Switches are used where it is desirable to control the light level. They commonly provide continuous control from off to full brightness. Special fixtures are necessary for dimmer control of fluorescent lights.

Time-delay switches, which allow a fixed or variable time from the time the switch is operated until the lights are turned out, are sometimes used for bedroom, garage, or outdoor lights.

Motion sensor switches are often used to control outdoor security lighting, or lights on porches, garages, and driveways.

Weatherproof switches are housed in a water-tight box and operated by a handle extending through a gasketed opening.

ELECTRICAL SAFETY

A safe wiring system offers protection against electrical shock and fire, and should meet the following requirements:

- All electrical materials and appliances used in the house should bear the label of the Underwriters Laboratories, Inc., a non-profit testing organization sponsored by the National Board of Fire Underwriters.
- The wiring system should meet the requirements of the National Electric Code, local building codes, and the utility company furnishing the power. Compliance with these codes should result in a reasonably safe system if properly maintained.

Grounding

A proper grounding system is important for safe operation of the electrical system and equipment. The local utility company should be consulted for requirements in addition to the following:

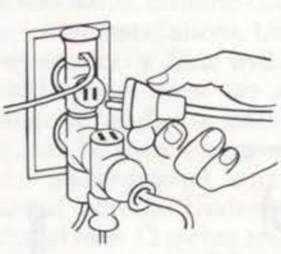
- Provide a conductor from the service disconnect to a metal water pipe, if available, or to any metal frame or reinforcing rods in the concrete foundation.
- If there is no metal water pipe, metal building frame, or reinforcing bars, provide a driven ground rod at the service entrance, with an unspliced conductor connecting it to the neutral conductor at the meter base.
- Provide a jumper around the water meter.
- Bond any metal water pipe to the gas piping, metal air ducts, sewer piping, metal siding, and any other metal objects to provide additional safety.
- When using plastic cable or conduit, include a grounding conductor to connect to metal boxes and grounding-type receptacles.
- When using metal conduit, make sure all connections are tight.

It is common to use a device called a surge protector with electronic equipment such as computers. For this device to protect the equipment, it must be connected to a grounded receptacle, not to a three-prong adapter or ungrounded GFCI.

Flexible Cords

Cords for lamps, portable tools, work lights, irons, and heaters are made with stranded rather than solid wire for greater flexibility. The wires are insulated with plastic or rubber. The wire size used varies from number 18 for lamps and small appliances to number 8 or 6 for major appliances.

Extension cords are used when the connecting cords of appliances are not long enough to reach a convenient receptacle. It is good practice to limit extension cords in the house to 10 feet. If the cord is too long or too small, it contributes to voltage drop and wasting of power, and can present a fire hazard if greatly overloaded.



The "octopus" presents a fire hazard as well as causing inconvenience.

All appliances and electrical devices should be approved or listed by Underwriters Laboratories, Inc. Be sure the approval refers to the equipment and not just to the appliance cord.

Power tools used in damp locations should be double-insulated or be equipped with a three-prong grounding-type plug to avoid shock caused by an internal short